NACA

RESEARCH MEMORANDUM

SPAN LOADINGS DUE TO WING TWIST AT TRANSONIC AND SUPERSONIC SPEEDS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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SUMMARY

Two similar tapered sweptback plan forms with the same two spanwise variations of twist have been tested in the Mach number range from 0.8 to 2.0. The test results showed, in general, rather good agreement with theoretical predictions of the incremental span loadings due to twist for zero angle of attack. The measured incremental span loadings due to twist generally diminished with increasing angle of attack through the Mach number range. At a Mach number of 0.9, the incremental loadings progressively vanished from the tip inboard with increasing angle of attack. For the highest angles of attack (about 20°) at Mach number 0.9, there was no difference in the span loadings of the flat and twisted wings. At the higher supersonic speeds, a similar vanishing at the tips of the incremental loading due to twist was starting at the highest angles of attack (near 20°).

For angles of attack lower than about 20° at supersonic speeds, no important change in the shape of the incremental loadings occurred, although the strength of the loading diminished with increasing angle of attack.

INTRODUCTION

The thin wings of modern high-speed airplanes deform appreciably in flight. The changes in air loading due to these deformations have not been extensively investigated. An aerodynamically important form of deformation is twist, or change in angle of attack at a given spanwise station on a wing. As part of a research program on the loads due to wing twist, two simple spanwise twist distributions have been tested at the Langley Aeronautical Laboratory in the Mach number range from 0.8 to 2.0. For a complete airplane with stores and nacelles acting on the wing, the twist distribution along the span may be rather complicated. It is hoped that the loadings due to simple twist distributions will, by superposition, give the loadings due to complicated distributions.

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SYMBOLS

A	aspect ratio
b	span
c	chord
c_{AV}	average chord
c_n	section normal-force coefficient
M	Mach number
q	dynamic pressure
t	thickness
x	chordwise distance
y	spanwise distance
α	angle of attack
Δc_n	incremental normal-force coefficient
Δp	incremental lifting pressure
$\Lambda_{c/4}$	sweepback at quarter chord
λ	taper ratio

MODELS

The wings tested and the twist variations which were built in are shown in figure 1. The wings tested at transonic speeds had an aspect ratio of 4, 45° of sweepback at the quarter chord, and a taper ratio of 0.15. The semispan wing tested at supersonic speeds had an aspect ratio of 3.5, 50° of sweepback at the quarter chord, and a taper ratio of 0.20. The thickness of the transonic wings varied from 6 percent at the body center line to 3 percent at and beyond halfway to the tip. The thickness of the supersonic wings was a constant 5 percent. A small camber was built into the transonic wings. All the wings tested had the same 65A-series thickness distribution and the same spanwise variations of built-in twist. The twist angle at the tip was 6°, in every case, which is attained by a linear and quadratic variation with spanwise position. The tips are at a lower angle of attack than the root, or washed out, for the positive direction assumed in this paper. Flat wings were tested in each speed range to provide a reference to which the twisted wings might be compared.

INCREMENTAL LOADING

Figure 2 shows the span loadings on the flat wing and the linearly twisted wing at $M = 1.6$ and at $\alpha = 12^{\circ}$. The difference in these span loadings, or incremental span loading, is also shown. Incremental span loadings formed in the same manner will be the basis of comparison between linear theory and the test results at the other Mach numbers and angles of attack.

The incremental loading shown in figure 2 is the isolated effect of spanwise wing twist with, of course, the nonlinear influence of angle of attack and thickness neglected. If real wings behave as do the wings of linear theory, the incremental loading for a given spanwise twist distribution will not change with angle of attack. For this case the increment in normal force produced by 6° of twist is 13 percent of the flat-plate normal-force coefficient. This illustrates the fact that, for a given overall accuracy in predicting the loading on a twisted wing, the accuracy of prediction of the incremental loading can diminish as the angle of attack increases.

PREDICTIONS AT ZERO ANGLE OF ATTACK

In order to eliminate, as far as possible, the influence of angle of attack, the root angle of attack may be set to zero. The predicted and measured incremental span loadings due to twist with the root angle of attack set to zero are shown in figures 3 and 4.

Wings With Linear Twist

Transonic speeds.- Figure 3 shows the comparative theoretical and experimental incremental span loadings for the transonic linearly twisted wing. The section loading parameter $\Delta c_n \, c/c_{AV}$ is plotted against the spanwise position $2y/b$, and the vertical dashed line indicates the spanwise position of the wing-body juncture.

At $M = 0.90$, the agreement between the data and theory is fairly good. The theory shown is a lifting-surface theory with a provision for approximating the presence of the body. (See ref. 1.) The prediction is better outboard than it is nearer the body.

At $M = 1.20$, there is close agreement between the data and theory, even though the validity of linear theory is becoming questionable as the Mach number approaches one. The theory used at supersonic speeds for subsonic leading edges is that given in references 2 and 3. In addition, the boundary conditions were only approximately satisfied in the theoretical computations for the transonic wings at $M = 1.20$. On the experimental model the variations of spanwise twist started near the wing-body juncture ($2y/b = 0.10$). However, the supersonic theory used was for variations from the center line. In order to account for this discrepancy, a solution was used for this case which had nearly zero average twist in the region of the body ($0 \leqq 2y/b \leqq 0.10$) and correct tip twist. Maximum deviations from the correct boundary conditions of 0.3° (about 5 percent of the tip twist) resulted at the center line and wing-body juncture, respectively. No attempt was made to account for the presence of the body. A feature of the results at $M = 1.20$ is the apparent absence of any marked influence of the body on the incremental span loadings.

Supersonic speeds.- Figure 4 shows the incremental span loadings with zero root angle of attack for the supersonic linearly twisted wings at $M = 1.6$ and 2.0.

Figure 4 shows that the data are about 20 percent lower than predicted values. As predicted, the loading is slightly weaker at the higher Mach number. The shock waves caused by the thickness seem to have no more effect on the span loadings at $M = 2.0$ than at $M = 1.6$, although the leading edge is supersonic at $M = 2.0$ and shock waves due to thickness must certainly be more severe. The theory used at $M = 2.0$ is given in reference 4.

Wings With Quadratic Twist

Transonic speeds.- Figure 5 shows the incremental span loadings on the wings with quadratic twist as measured and predicted at transonic speeds.

The agreement with theory is again rather good at $M = 0.90$. The agreement at $M = 1.20$ is about the same as it was in the case of the wings with linear twist. For the theoretical computations a small amount of cubic spanwise twist was introduced, again the twist being correct near the tip. In this case maximum deviations from the correct boundary conditions were 0.1°, or less than 2 percent of the tip angle. Again there is no apparent body effect at $M = 1.20$.

Supersonic speeds.- Figure 6 shows the predicted and measured incremental loadings for the wing with quadratic twist at $M = 1.6$. Data for $M = 2.0$ are not yet available.

The agreement is better in this case than it was for the linearly twisted wing at this Mach number. The values are only 7 percent lower as compared with about 20 percent for the wing with linear twist. This must be partly due to the fact that the average angle of twist over the plan form is lower than it was in the case of the linearly twisted wings.

LIFTING PRESSURE DISTRIBUTIONS

Figure 7 shows the chordwise lifting pressure distribution corresponding to two of the incremental span loadings previously shown. The lifting pressure coefficient $\Delta p/q$ is plotted against the chordwise position x/c; distributions are for Mach number 1.6, zero root angle of attack, and the spanwise station at which the data were taken is 0.7 of the semispan. Distributions for both linear and quadratic twist are shown. These distributions are typical of other spanwise stations at this Mach number. Linear-theory predictions of the lifting pressure are shown for both twist variations.

For the wing with linear twist, the agreement with theory is good. The level of agreement is comparable to that indicated by recent pressure measurements made on a zero-thickness delta wing. (See ref. 5.) Since a zero-thickness delta wing exactly satisfies the boundary conditions of linear theory, the agreement with theory obtained on such a wing typifies the best that can be expected. To have similar agreement on a wing with 5-percent thickness is surprising. The agreement for the wing with quadratic twist is even better than that for the wing with linear twist. The fine agreement shown here was reflected in the good agreement observed in the integrated loadings for the wing with quadratic twist.

PREDICTIONS AT ANGLE OF ATTACK

All the incremental loadings that have been shown thus far were for zero root angle of attack. According to the linear theory, the incremental loadings will not change with angle of attack, or, in other words, the twist will produce the same change in loading whether or not the wing is at an angle of attack. Of course, this simple prediction is not borne out by the data.

Transonic Speeds

Figure 8 shows the effect of angle of attack on the span loadings at $M = 0.90$. In this figure, instead of incremental loadings, the total span loadings are shown for the flat and linearly twisted wings. Data for angles of attack of 4°, 8°, and 12° are shown. For the transonic wings at angle of attack, incremental aeroelastic twists occurred which amounted to about 10 percent of the 6° of built-in twist at 12° angle of attack. Figure 8 shows that the shape of the incremental loadings (the vertical difference between curves) changes markedly with angle of attack while the strength of the incremental loading greatly diminishes. At $\alpha = 4^{\circ}$, both wings show the same sort of span loading, the wing with linear twist carrying the lesser load. Between $\alpha = 4^{\circ}$ and $\alpha = 8^{\circ}$, the flow separates at the tip of the flat wing, and at $\alpha = 8^{\circ}$ the flow is separated outboard of about 60 percent of the semispan. The twisted wing at $\alpha = 8^{\circ}$, however, has much the same type of span loading as at $\alpha = 4^{\circ}$ and the flow appears unseparated. At $\alpha = 12^{\circ}$ both wings are separated outboard of about 40-percent semispan. The incremental loading, already small at $\alpha = 12^{\circ}$, effectively vanishes at the higher angles of attack. At the higher angles, then, there is no difference between the flat and twisted wings. Similar results have been obtained on the wing with quadratic twist. At Mach number 1.2 the results are consistent with those to be shown for the supersonic wings, but values will not be presented.

Supersonic Speeds

In figure 9, the percent of the theoretical loading which must be used to obtain a good fairing through the data in the outboard regions (beyond half span), where most of the incremental lift is located, is plotted against the root angle of attack. The most striking feature of this plot is the rapid decrease of the effective linear twist with angle of attack. There is no marked effect of the Mach number, although the $M = 2.0$ data are for a supersonic leading edge and the $M = 1.6$ data are for a subsonic leading edge. As was mentioned previously, a less accurate prediction of the incremental loading is acceptable at the higher angles of attack. Even if 100 percent of the theoretical loading for the linear twist were used to predict the loading at 12° angle of attack, the 45-percent difference indicated by figure 9 would come to an error of about 12 percent in predicting the total loading. A better estimate of the incremental loading, such as the fractions of the theoretical loading indicated by the curves, could lead to a negligible error in the total loading.

For the wing with quadratic twist, only the $M = 1.6$ data, or subsonic-leading-edge data, are available. However, there is no reason to expect that the Mach number effects will be any stronger than they were for the linearly twisted wing. For the wing with quadratic twist, figure 9 shows that the good prediction of the incremental loading at zero angle of attack is coupled with a slow drop in effective twist as the angle of attack increases. This contrast with the relatively poorer prediction at zero angle of attack and more rapid drop with angle of attack observed on the linearly twisted wing.

There is little change in the shape of the incremental loadings from 12° angle of attack to about 20°. In the neighborhood of 20°, incremental loadings vanish on the outboard regions of the wing in a manner similar to that observed at $M = 0.90$.

CONCLUDING REMARKS

At higher subsonic speeds the theoretical predictions at zero angle of attack of incremental span loads due to twist were fairly good. Because of separation effects, these predictions failed as the angle of attack increased. At the highest angles, there was no difference in the loadings of the flat and twisted wings. At low supersonic speeds, the predictions at zero angle of attack were better although the validity of the linear theory is becoming questionable. At the higher supersonic speeds, the predictions at zero angle of attack were generally larger than the actual loadings. The prediction was better for the wings with lower average twist. At angles of attack up to 12°, factors were applied to the theoretical incremental loading which give good agreement with the data. Through the Mach number range of 0.9 to 2.0 the incremental loading steadily diminished with angle of attack.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 5, 1957.

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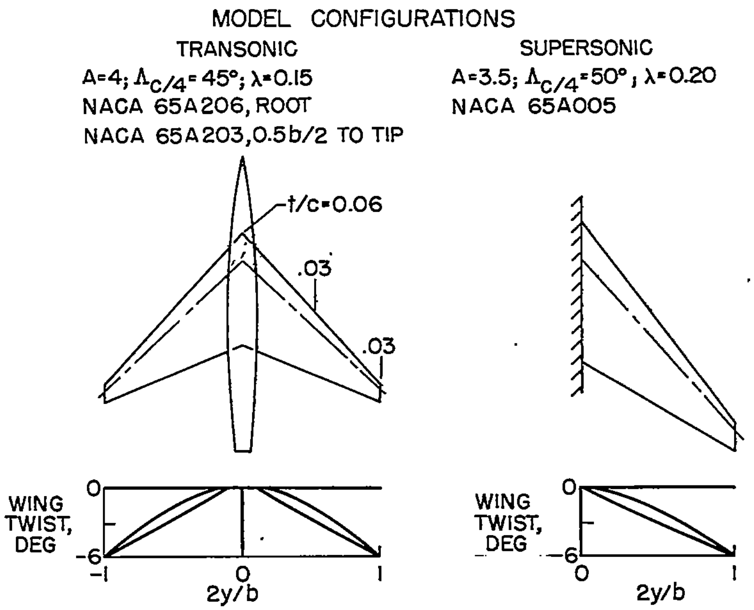

Figure 1

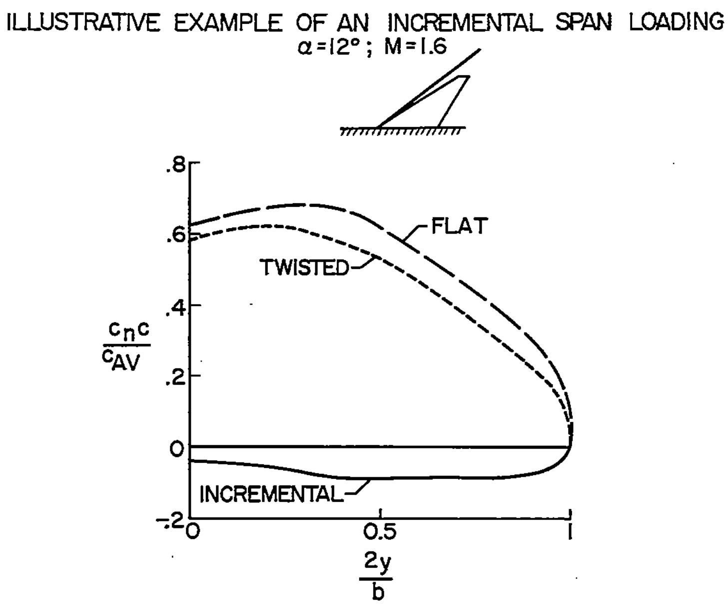

Figure 2

INCREMENTAL SPAN LOADINGS ON WING WITH LINEAR TWIST

$\alpha = 0°$

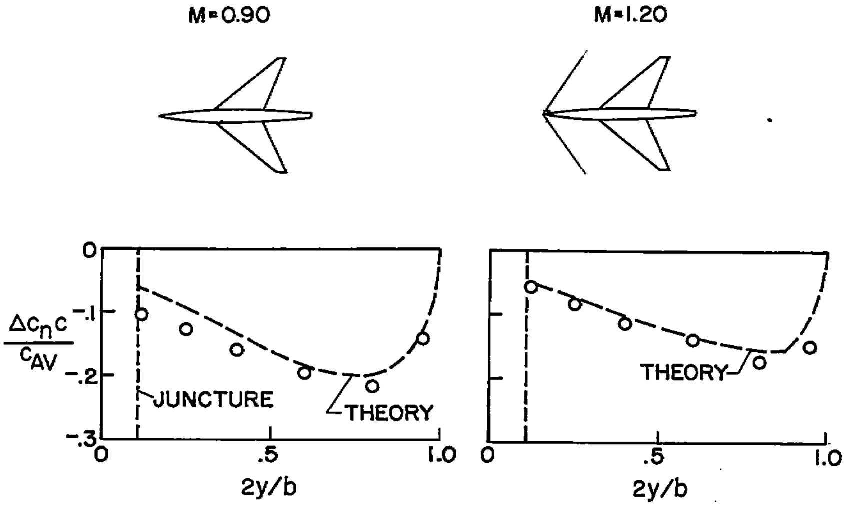

Figure 3

INCREMENTAL SPAN LOADINGS ON WING WITH LINEAR TWIST

$\alpha = 0°$

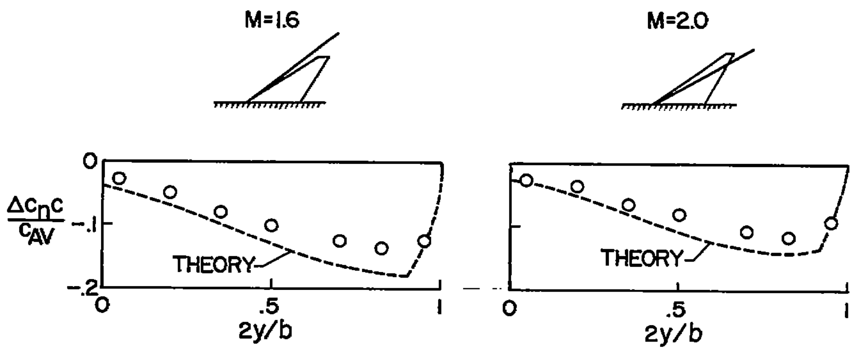

Figure 4

INCREMENTAL SPAN LOADINGS ON WING WITH QUADRATIC TWIST

$\alpha = 0°$

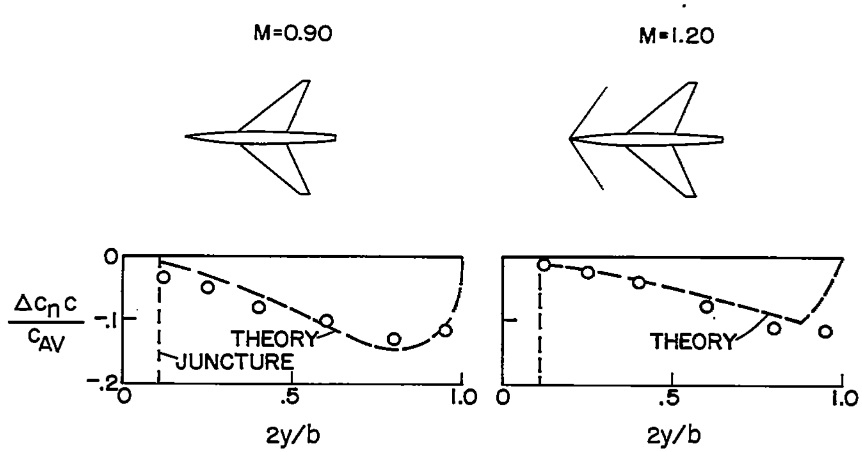

Figure 5

INCREMENTAL SPAN LOADINGS ON WING WITH QUADRATIC TWIST

$\alpha = 0°$; M=1.6

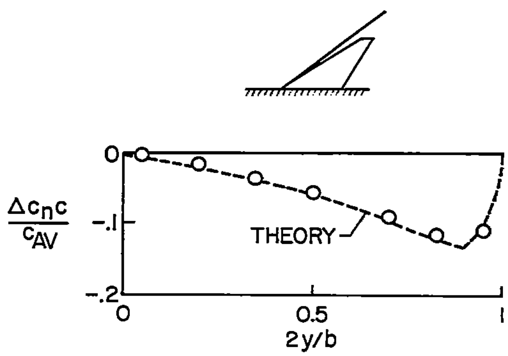

Figure 6

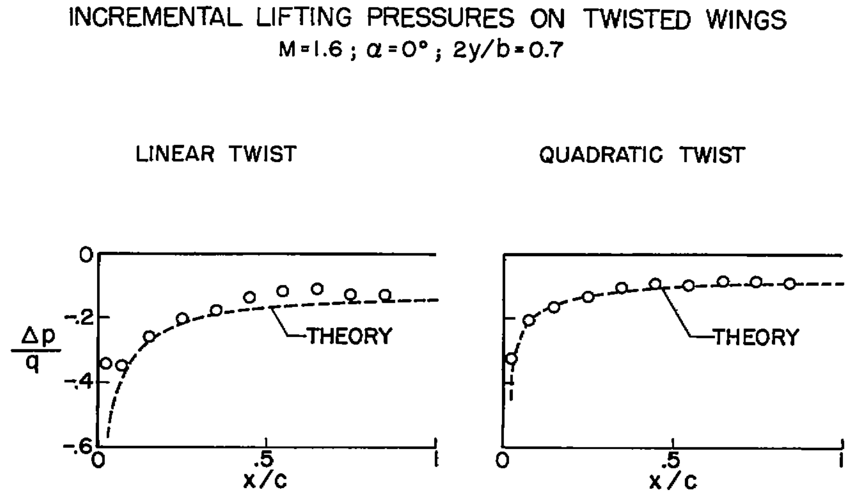

Figure 7

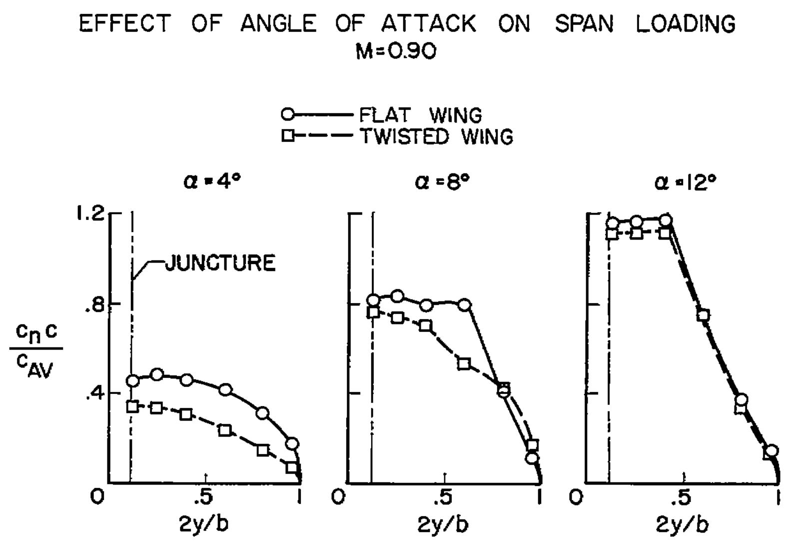

Figure 8

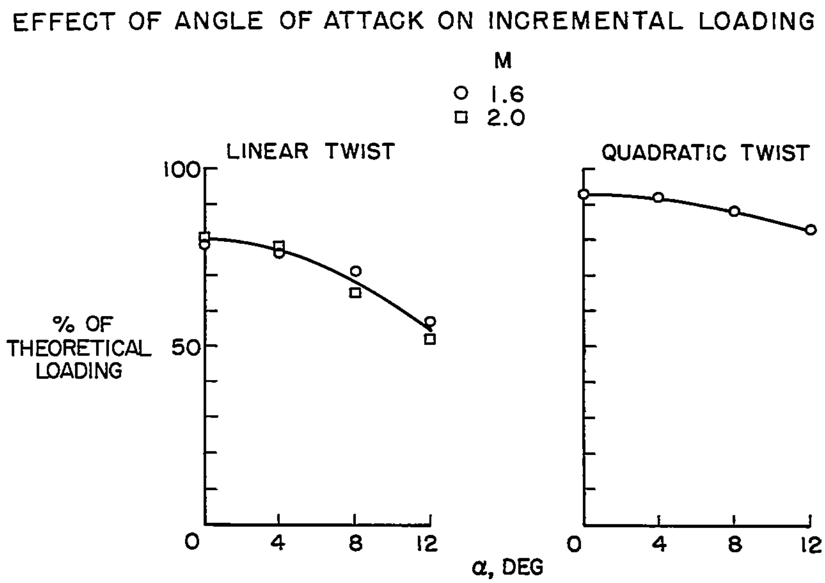

Figure 9

NACA - Langley Field, Va.